Study of flow of superfluid He-II very near T_λ

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Abstract

We report here, preliminary data from an experiment studying flow of superfluid helium through a slit orifice (of sub-micron width) very close to T_λ. Critical supercurrent (I_c) data is obtained from a step function drive to the diaphragm in a Helmholtz resonator cell. The superfluid density (ρ_s) data can be obtained from the resonant frequency of the Helmholtz oscillator, as determined by transfer function of the resonator or from the free ringing after the step function excitation. Preliminary data shows that $I_c \sim \rho_s^{1.27}$ and $\rho_s \sim \tau^{0.73}$, where τ is the reduced temperature. However, the magnitude of I_c is much larger than expected, indicating a possible parallel flow path. Further investigations are in progress.

Keywords: superfluid; hydrodynamics; critical exponent

Flow of ^{4}He through small channels very close to T_λ is interesting in several aspects. First, the critical velocity can be expected to vary with temperature as inverse of the coherence length, ξ. Secondly, as the ξ becomes comparable to the size of a flow channel, one may expect to observe Josephson effect.

We are aware of three measurements of critical current close to T_λ. In the first [1], the critical velocity (v_c) through filter materials with 2 and 10 μm pores as a function of temperature fit the form $v_c \sim \tau^\nu$ with the critical exponent, $\nu = 0.68$ down to $\tau \approx 10^{-4}$. Later measurements of v_c through 0.03, 0.1 and 0.4 μm pores fit $\nu = 0.5$ down to $\tau \approx 10^{-4}$ [2] and through a short aperture of 12.5 μm, fit a ν of 0.5 was down to $\tau \approx 10^{-3}$ [3]. Renormalization group (RG) theory predicts $\nu = 0.68$.

The Josephson effect has been observed in superfluid ^{3}He[4,5]. In ^{4}He one has to approach T_λ to within $\tau \sim 10^{-6}$ in order for the ξ to be comparable with the dimensions of an aperture of practical size.

Our cell is conceptually very similar to one described in Ref.[4]. To minimize dissipation and to assure a high quality factor, copper powder was sintered into pockets in the cell body. The cell is installed into the crysostat with several temperature controlled stages. Two last stages are controlled by high-resolution thermometers[6] with a nK temperature stability of the last stage. A lamda-point device, which allowed calibration of T_λ is installed on the same stage as the cell, 14.3 cm below the aperture level. The cell is separated from the room-temperature aparatus by a cryovalve.

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The aperture is a rectangular slit with a dimension of $0.19\mu m \times 2.9\mu m$. It was made by e-beam lithography and reactive ion etching in a $\approx$100 nm thick SiN membrane. A $\approx$20 nm Ti/Au double layer evaporated on each side of the membrane, forms a pair of electrodes, allowing application of the electric field to the aperture.

An application of a step-voltage to the diaphragm drives a flow through the aperture. The time-derivative of the diaphragm position gives the current through the flow path. The diaphragm position with respect to the new equilibrium position gives the pressure differential. The frequency of the Helmholtz oscillations at the end of such a transient is measured to give the superfluid density. In addition, the Helmholtz frequency is separately measured from the diaphragm response to an ac drive voltage.

The current-phase characteristic, $I(\Delta P)$, is fairly well fitted by a model consisting of a non-linear element with $I \sim \text{arcsinh}(\Delta P/P_0)$ in series with linear inductance, together with small flow due to normal fluid and dissipation due to thermomechanical effects. One unexpected observation is presence of large offset current through the flow path, for which we do not have an adequate explanation. This, and variation of temperature dependences between different runs may be caused by large heat currents due to a leak in the cryovalve.

To quantify the measurements of the critical current we sample either fit function or experimental current-phase characteristics at small pressure (1 mPa). The results are shown on the Fig. 1 as a function of resonance frequency of the Helmholtz oscillator squared ($\sim \rho_s$). Various curves are explained in the caption. We have also measured $\rho_s \sim \tau^{0.73}$, leading to critical velocity $v_c \sim \tau^{0.54}$. We note that, although $\rho_s(\tau)$ and $v_c(\tau)$ dependencies can be affected by temperature differences between the thermometer and the cell, $I(\rho_s)$ can not.

Calibration of the absolute value of the critical current and the resonant frequency is based on the knowledge of the gap between the flexible diaphragm and the electrode, used to drive it. The gap has not been independetly measured. If we assume design value of 70 μm, then the critical current value at $\tau = 10^{-4}$ is $\sim$360 times too high and the frequency squared is $\sim$ 13 times too high. These values could be explained by a parallel path of crosssectional area (determined by I_c) of $a = 14\ \mu m^2$ and effective length (determined by the frequency and a) of 21 μm. However, a path of such a combination area and length is difficult to imagine.

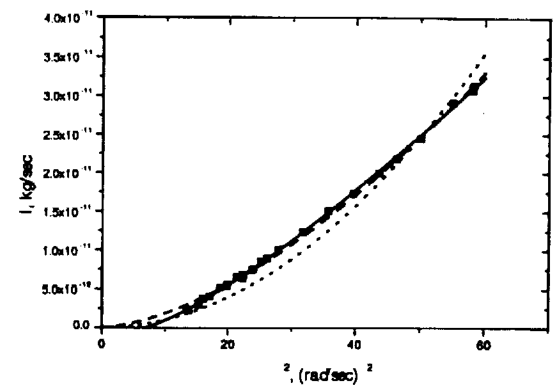

Fig. 1. Dependence of the critical current on $f^2 \sim \rho_s$. The solid line represent the best fit to $A(f^2 - x_0)^y$ with $x_0 = 6.75\text{Hz}^2, y = 1.27 \pm 0.03, A = 2.1 \cdot 10^{-13}$kg/sec, the dashed line is the fit with x_0 set to 0, $y = 1.61 \pm 0.02, A = 4.5 \cdot 10^{-14}$kg/sec and the dotted line is fit to the RG theory prediction: x_0 set to 0, y set to 2, $A = 9.9 \cdot 10^{-15}$kg/sec. The lowest ρ_s point is $\sim 30\mu$K from the T_λ.

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